

## **Model based Object Pose Refinement for Terrestrial and Space Autonomy**

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### **EXTENDED ABSTRACT**

Model-based object pose refinement algorithms have been applied to rack stacking and pallet loading/unloading in the context of automated forklift operations in a warehouse environment. These model-based pose refinement algorithms enable high-precision alignment by utilizing known geometric object models and their salient straight line edges in matching 3-D graphic models to actual video images. Setups using one and two cameras were compared to assess the ability of each configuration to accurately estimate the pose of a pallet or a rack containing material to be transported or stacked. An analysis of pose error covariance has been performed to examine pose estimate precision and a comparison of pose estimates to manual measurements has allowed a quantification of absolute accuracy. The algorithms implemented have actually been incorporated into a CMU/NREC facility with successful demonstrations of rack stacking and pallet loading/unloading operations. Also, by combining the above pose uncertainty algorithm with an algorithm that checked for maneuverability constraint violations of the vehicle, the probability of success of that particular scenario could be determined before it was actually attempted. The localization algorithms implemented have also been successfully tested for Orbital Replacement Unit (ORU) module insertion and these same algorithms could also be applied to such space applications as autonomous space assembly and various stages of sample return.

### **1. Automated Rack Stacking**

In conventional model-based computer vision, camera calibration and object localization are performed sequentially. This sequential update cannot compensate for the inaccuracy in initial camera calibrations. Earlier we developed a new 18-variable weighted least-squares algorithm that updates both camera and object models simultaneously for given two camera views of two mating objects. This simultaneous update enables accurate model matching even with rough, approximate initial camera calibrations. Since the rack is usually very large, two cameras are needed for object pose determination. One camera sees only the left-side rack leg, while the other camera sees only the right-side rack leg. The relative orientation between two cameras is about 90 degrees in diverging directions for this rack stacking application, and thus it is difficult to get accurate relative camera calibration between the two cameras. This is why the simultaneous update algorithm that compensates for inaccuracies in camera calibrations is needed to achieve high-precision rack stacking.

In our initial testings, two rectangular fiducial marks were attached on the front and side surfaces of each leg. Each camera view image sees two orthogonally located rectangles with eight edges. The covariance error analysis of the rack pose estimate standard deviation using real images indicates that the estimate error is within 1.5 cm and 2 degrees.

### **2. Pallet Loading/Unloading**

A fork hole detector that identifies edges of a pair of fork holes from a given camera image of a pallet has been implemented. The detector goes through the following five steps: 1) Canny edge detector, 2) Lowe's straight line detector, 3) merge straight image lines, 4) find rectangles using parallelism conditions, 5) detect the best-

match rectangle pair with the highest match score. After detecting fork hole edges, the pallet pose is then determined by either a one-view object localization algorithm or a two-view simultaneous update algorithm.

Pallet images with fork holes were obtained for 5 pallet orientations ranging from  $40^\circ$  to  $+40^\circ$  yaw at 4 different distances ranging from 2 to 5 meters. In a laboratory setup with good lighting/imaging conditions, the implemented fork hole detector detected the fork holes 100% without difficulty. Thereafter both one-camera-view and two-camera-view object pose algorithms were applied. The results indicate that in pallet loading/unloading applications, one-camera-view object localization is sufficient. At a distance of 5 meters, it yielded 2 cm position error and 4 degrees orientation error. At a distance of 2 meters, it yielded 0.5 cm position error and 1 degree orientation error. Insight was gained into the performance of the estimation algorithm as a function the number and orientation of the lines extracted from the image. Seemingly insignificant variations in the line detection output could result in drastic changes in the ability of the pose estimation algorithm to accurately estimate the pose.

Integration of the above mentioned covariance analysis with a maneuverability constraint algorithm was done in order to create an algorithm for predicting the probability of success for the given conditions. The uncertainty values calculated by the pose estimation algorithm are used to do a grid calculation of maneuverability constraint violations and then calculates the probability of success from the ratio of successes to attempts. This algorithm could be used as part of a higher level risk assessment for vehicle behavior decisions.

### **3. ORU Module Insertion for Space Station Applications**

An immediate potential application of the two-view simultaneous update object pose refinement algorithm is for International Space Station (ISS) robotics, since the camera viewing problem is a concern in ISS telerobotic operations and vision system assistance is needed for high-precision alignment. For instance, during the orbital replacement unit (ORU) insertion task, the end effector close-up camera view is occluded by the ORU, while the overhead and other cameras provide limited views. Due to this visual occlusion and limited viewing problem, it is often difficult to ensure baseline manual teleoperation to reliably maintain the alignment within the precision requirement. For example, the alignment requirement for ISS remote power controller module (RPCM) ORU insertion is  $\pm 1/4$  inch for each translation axis and  $\pm 3$  degrees for each rotational axis.

### **4. Potential future applications in Mars Sample Return**

Object pose estimation is essential in many of the stages involved in a Mars Sample Return mission. In a few of these, a priori information (i.e., physical dimension) about the object whose pose needs to be determined clearly makes a model-based technique very attractive. A rover returning to the lander to deposit the collected samples is one such situation. Another is the autonomous rendezvous between the sample orbiting Mars and the retrieval probe. These scenarios could greatly benefit from the model-based pose estimator used in the algorithms above.

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